

Development of Trace Contaminant Control Prototypes for the Primary Life Support System (PLSS)

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Results are presented on the development of Trace Contaminant Control (TCC) Prototypes for use in Extravehicular Activities (EVAs), and more specifically in the Primary Life Support System (PLSS). The current TC-control technology involves the use of a packed bed of acid-impregnated granular charcoal, which is non-regenerable, and the carbon-based sorbent under development in this project can be regenerated by exposure to vacuum at room temperature. Data on sorption and desorption of ammonia and formaldehyde, which are major TCs of concern, as well as pressure-drop calculations were used to design and test 1/6-scale and full-scale trace contaminant control system (TCCS) prototypes. Carbon sorbents were fabricated in both the granular and foam-supported forms. Sorbent performance was tested for ammonia sorption and vacuum regeneration in 1/6-scale, and pressure-drop characteristics were measured at flow rates relevant to the PLSS application.

Nomenclature

<i>acfm</i>	=	actual cubic foot per minute
<i>AFR</i>	=	Advanced Fuel Research, Inc.
<i>cfm</i>	=	cubic foot per minute
<i>CO₂</i>	=	carbon dioxide
<i>C_{SMAC}</i>	=	24-hour space flight maximum allowable ammonia concentration (g NH ₃ /cm ³)
<i>D</i>	=	bed diameter (mm)
<i>D_p</i>	=	particle diameter (mm)
<i>EVA</i>	=	extravehicular activity
<i>f</i>	=	Fanning friction factor (-)

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H	= height (mm)
H_2O	= water
K	= friction parameter: $K = f/D_p$
L	= length (mm)
m_c	= carbon weight (g)
\dot{m}_{gen}	= ammonia mass generation rate (mg/h)
<i>NASA</i>	= National Aeronautics and Space Administration
NH_3	= ammonia
O_2	= oxygen
<i>PLSS</i>	= primary life support system
<i>ppi</i>	= pores per inch
<i>PVDC</i>	= polyvinylidene chloride
<i>RCA</i>	= rapid cycle amine
<i>RH</i>	= relative humidity (%)
<i>SLPM</i>	= standard liter per minute
<i>SMAC</i>	= spacecraft maximum allowable concentration
<i>STP</i>	= standard temperature and pressure
t	= time (h)
t_{R0}	= minimum apparent residence time within bed required to obtain a high or near optimal capture efficiency (h)
<i>TC</i>	= trace contaminant
<i>TCC</i>	= trace-contaminant control
<i>TCCS</i>	= trace contaminant control system
<i>UTAS</i>	= UTC Aerospace Systems
v_0	= superficial gas velocity (m/s)
V_F	= sorbent volume; full scale (cm^3)
V_L	= sorbent volume; laboratory scale (cm^3)
W	= width (mm)
ΔP	= pressure drop (in H_2O , Pa, psi, mm Hg)
ρ	= gas density (g/cm^3)
ρ_B	= sorbent-bed bulk density (g/cm^3)
ζ	= ammonia-sorption capacity (g NH_3 per g carbon)

I. Introduction

THE future of space exploration is critically dependent on regenerable life support systems. This study addresses the development of trace contaminant control system (TCCS) prototypes based on regenerable carbon sorbents for trace-contaminant (TC) removal for the space suit used in extravehicular activities (EVAs). Paul and Jennings¹ reviewed the current state of the art and historical approaches to TC removal in the Primary Life Support System (PLSS), often referred to as the space suit backpack. Activated carbon (charcoal) was identified as a preferred sorbent for the TCCS in terms of effectiveness, simplicity, and maturity of this technological solution. Carbon regeneration, however, has always been problematic, mainly because all carbons used to date were impregnated with phosphoric acid or other acidic compounds. In the current TCCS, granular activated carbon called Ammonasorb II is used to adsorb TCs, and especially ammonia, which is the main trace contaminant of interest. The carbon is impregnated with phosphoric acid to ensure strong ammonia sorption, but this also makes regeneration difficult. Temperatures as high as 200 °C were shown to be required for only partial desorption of ammonia on time scales of 18–140 hours,¹ which makes regeneration difficult. Thus, the activated carbon has been treated as an expendable resource and the sorbent bed has been oversized to last throughout the entire mission (23 kg carbon for cabin-air revitalization and about 0.45 kg for the space suit).

Another important consideration in the design of TC sorbents and systems is pressure drop. Granular sorbents offer significant resistance to gas flow, which is associated with a high demand for fan power. Thus, a monolithic structure (e.g., a honeycomb), or a sorbent in the form of open-porosity foam, is desirable to reduce the pressure drop.

Recent work on trace-contaminant control led to the conclusion that ammonia and formaldehyde are the only two trace contaminants the concentration of which can exceed the Spacecraft Maximum Allowable Concentration (SMAC).² Although adsorption of ammonia on activated carbon has been studied extensively,^{1,3–9} the adsorption of

formaldehyde on carbon, especially in the presence of ammonia, water, carbon dioxide, and oxygen, attracted attention only recently⁹. The objective of the present study was to develop and perform preliminary testing of 1/6-scale and full-scale TCCS prototypes suitable for use in the PLSS. Design specifications for the full-scale prototype are: (1) a flow rate of 170 L/min, STP; (2) maximum TCCS dimensions: 11.5" x 1.8" x 7.0" (29.2 cm x 4.6 cm x 17.8 cm); (3) maximum pressure drop: 0.10 in H₂O ($2.5 \cdot 10^{-4}$ atm = 0.19 Torr) at 4.5 acfm (127 L/min); and < 0.20 in H₂O ($2.5 \cdot 10^{-4}$ atm = 0.37 Torr) at 6.0 acfm (170 L/min); and (4) maximum duration of a single EVA: 8 hours (the amount of sorbent must be sufficient to support at least one EVA).

The carbon sorbent used in prototype development was described in our previous work.⁵⁻⁷ The high-purity, microporous carbon was obtained by carbonization of polyvinylidene chloride (PVDC), which was followed by thermal oxidation by exposure to air at temperatures below 400 °C. It is believed that good TC-sorption capacity can be accomplished through the combination of: (1) a particularly favorable pore structure (microporosity, i.e. pores smaller than 2 nm) for optimum physical adsorption (physisorption) of TCs; and (2) carbon-surface conditioning that enhances adsorption without adversely affecting vacuum regeneration. Such enhancement of ammonia-sorption capacity by thermal oxidation of the carbon surface was reported previously.⁵⁻⁸ Furthermore, the avoidance of acid impregnation of carbon helps the cause of adsorption reversibility. Finally, the issue of pressure drop and fan-power requirement is addressed through the use of a thin carbon sorbent layer deposited on a vitreous carbon foam structure with fairly open porosity (60 pores per inch). Prototype TCCS assemblies were constructed using such PVDC-derived carbon, which was supported on vitreous carbon foam, and also a more traditional packed bed of granular sorbent of similar PVDC carbon.

II. Materials and Experimental Techniques

A. Carbon Sorbent Supported on Vitreous Carbon Foam

The sorbent used in this study was obtained by carbonization of PVDC procured from Goodfellow. The sorbent support employed in this work was Duocel[®] foam manufactured by ERG Aerospace Corporation. This foam is described as an open-cell, porous structure consisting of an interconnected network of solid “struts,” the porosity of which is determined by the number of pores per inch (ppi). 60 ppi foam was used in this study. Prior to use, the foam was subjected to thermal heat treatment at 1,350 °C for 60 minutes in a flow of nitrogen in order to thermally anneal the carbon and reduce its reactivity with oxygen. The carbon sorbent was prepared by loading a 0.20 g cylinder (22 mm in diameter and 12.5 mm thick) of vitreous carbon foam with 3.3 g of PVDC powder using the dry powder coating technique described in references^{5,6}. Carbonization was carried out in a tube furnace, in a flow of nitrogen, at 830 °C, and a hold time at the above temperature was 3 minutes.

B. Granular Carbon Sorbent

Granular sorbent obtained by carbonization of PVDC (BrightBlack[®] carbon) was provided by Entegris. The sorbent was in the form of cylindrical pellets 2.2 mm in diameter and 3.3 mm in height.

C. Carbon-Surface Treatment by Oxidation in Air

As described in references⁵⁻⁸, surface conditioning of the PVDC carbon via thermal oxidation at modest temperatures had a dramatic effect on ammonia adsorption. Unless stated otherwise, the sorbent was oxidized in ambient air at 350 °C for a period sufficient to achieve a PVDC carbon weight loss of about 50% (38 hours).

D. Experimental Set-up and Procedures for Sorbent Testing

The experimental set-up used for testing subscale prototypes at UTC Aerospace Systems (UTAS) is shown in Figure 1. Its operation is similar to the operation of the testing facility available at Advanced Fuel Research, Inc. (AFR) described in references^{5,6,8,9}, except that the UTAS rig is capable of handling much higher flow rates, in the case of this study 1.0 ft³/min. The system makes it possible to measure ammonia-adsorption capacity of carbon sorbents in the presence of carbon dioxide, oxygen and water vapor. The apparatus incorporates a Thermo Environmental Instruments Model 17C chemiluminescence ammonia analyzer, Tylan 0-30 SLPM mass-flow controllers (air), a General Eastern Hygro M4 with D2 sensor for humidity measurement, an Agilent 34970A Data Acquisition/Switch, and a gas manifold. Using mass flow controllers, the initial gas mixtures are blended to achieve the desired concentration of these gases (~20 ppm ammonia at the inlet). For humidifying the gas stream, the air is routed through a humidifier. During sorbent testing, the final mixture is first directed through a sample bypass line, to establish the baseline gas concentration and flow rate. It is then re-directed through the sample “cell” for the sorbent

adsorption testing. The ammonia-concentration and humidity data are collected during the run. The adsorber is then removed, weighed, and the sorbent is regenerated by connecting it to a vacuum pump overnight. The final pressure is then recorded and the adsorber containing the regenerated sorbent is weighed.

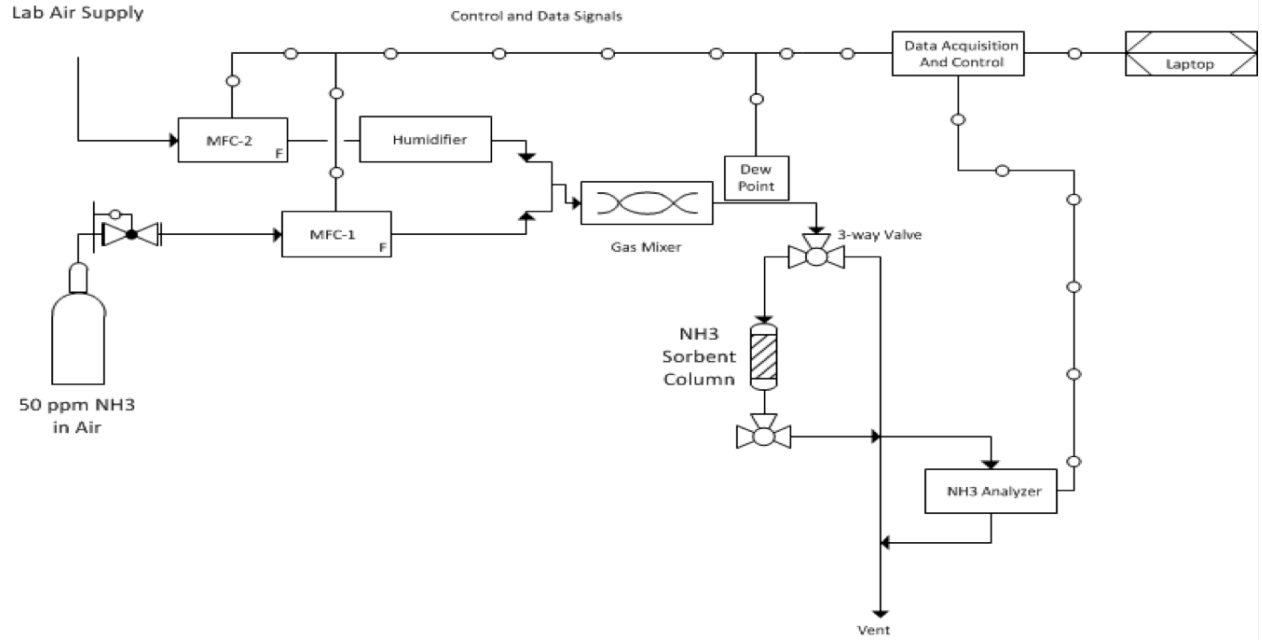


Figure 1. A test rig used for subscale prototype testing and ammonia sorption experiments at UTAS.

III. Results and Discussion

A decision was made that two types of PVDC-based sorbents will be tested: granular carbon and foam-supported carbon. The former design is more traditional, and thus associated with less risk, and it can serve as an immediate replacement for the state-of-the-art granular Ammonasorb II carbon. The foam-supported sorbent is more innovative, has a higher potential for better sorption and pressure-drop performance, but is more likely to be subject to unexpected challenges.

A. Development and Preliminary Testing of 1/6-Scale Prototypes

1. The Amount of Sorbent Required

The determination of the amount of sorbent required to maintain ammonia concentration at or below the SMAC level was based on the approach presented by Paul *et al.*¹⁰. If one disregards the ammonia loss due to RCA ullage, suit leakage, and CO₂ sensor losses, the following expression can be derived:

$$m_c = \frac{\dot{m}_{gen}}{\zeta} t + \frac{\dot{m}_{gen}}{C_{SMAC}} \rho_B t_{R0} \quad (1)$$

where

m_c carbon weight (g)

\dot{m}_{gen} ammonia mass generation rate (mg/h)

$\dot{m}_{gen} = 83 \text{ mg per 8 hours} = 0.010 \text{ g/h}^{11}$ (for a full-scale system for a single astronaut);
for a 1/6-scale prototype, $\dot{m}_{gen} = 0.010/6 = 0.0017 \text{ g/h}$

t time (h)

ζ measured ammonia-sorption capacity (g NH₃ per g carbon)

$\zeta = 19 \text{ mg NH}_3/\text{g}$ (foam-supported PVDC carbon)^{8,9,12}; $\zeta = 8.2 \text{ mg NH}_3/\text{g}$ (granular carbon)^{8,12};

ρ_B	measured sorbent-bed bulk density (g/cm ³) $\rho_B = 0.11 \text{ g/cm}^3$ (foam-supported PVDC carbon) ¹² ; $\rho_B = 0.526 \text{ g/cm}^3$ (granular carbon) ¹²
t_{R0}	minimum apparent residence time within bed required to obtain a high or near optimal capture efficiency (h) $t_{R0} = 0.25 \text{ s} = 6.9 \cdot 10^{-5} \text{ h}$ ¹³
C_{SMAC}	24-hour space flight maximum allowable ammonia concentration (g NH ₃ /cm ³) $C_{SMAC} = 14 \text{ mg/m}^3 = 1.4 \cdot 10^{-8} \text{ g/cm}^3$ ¹⁴

The above values of ammonia-sorption capacity, ζ , for granular and foam-supported sorbents are supported by our dry-gas data corrected for operation under humid-gas conditions^{8,9,12}. They show that, for the relative humidity between 30% and 40%, the sorption capacity is approximately 90%–120% higher than the corresponding values for dry-gas conditions. Thus a conservative multiplier of 1.7 was used to correct the ammonia-sorption capacity for the effect of humidity.

Eqn. (1), with the input parameters listed above for a 1/6-scale prototype, can be used to show that the required minimum amount of carbon for a single eight-hour EVA is 1.7 g (15 cm³) in the case of the foam-supported PVDC carbon, and 6.2 g (12 cm³) in the case of the granular sorbent. For five 8-hour EVAs, Eqn (1) gives the following amounts of carbon, again for a 1/6-scale prototype unit: 4.6 g (42 cm³) for the foam-supported PVDC carbon, and 13 g (25 cm³) for the granular sorbent.

It should be noted that the above estimates for the minimum sorbent amount required seem rather low, as was later confirmed by 1/6-scale sorption experiments discussed below, and it was felt that generous safety margins needed to be applied. In view of the above considerations, the following bed-enclosure dimensions were chosen for the 1/6-scale prototype: 7.4 x 5.0 x 2.5 cm (bed volume of 94 cm³), with the understanding that not all the internal enclosure volume needed to be used by the sorbent bed. Having determined the bed volume and dimensions, several system configurations were considered, as discussed below.

2. Design A: Deep Sorbent Bed with a Rectangular Cross-Section

Concerns about high pressure-drop, and pressure-drop calculations that confirmed these concerns, led to abandoning a tubular bed design in favor of a sorbent bed with a rectangular cross-section, as shown in Figure 2. It was decided that both 1/6-scale prototypes, the one containing the granular sorbent and the one with foam-supported carbon, will be housed in identical aluminum enclosures like the one depicted in Figure 2. Although not shown in the picture, all round holes are threaded. The two holes on the inlet/outlet ends are ½ inch pipe thread to accept a ½ inch pipe to AN (flared) adapter. The 20 small holes on the top are 4–40 blind taps for securing the cover plate (not shown). The overall housing dimensions (with cover plate), when scaled to full size, meet the NASA volume-allocation with reasonable margins. A nominal flow rate of 1 acfm (air or nitrogen) was meant to be used in 1/6-scale tests at UTAS.

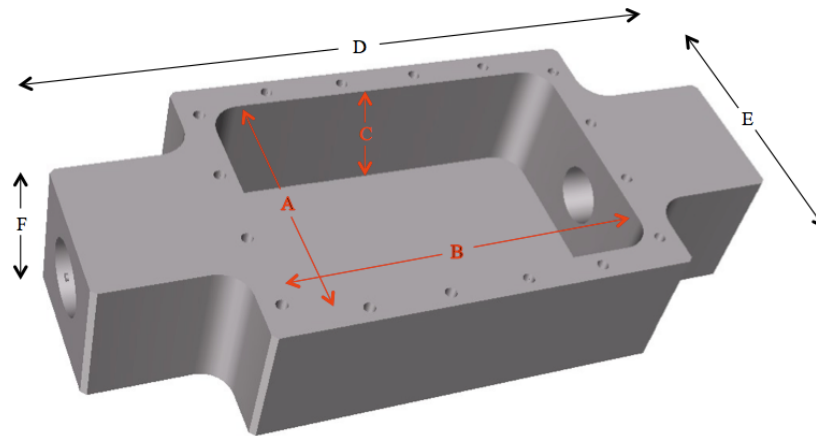


Figure 2. A 3-D drawing of the prototype sorbent assembly suitable for housing either granular or foam-supported carbon sorbent. The dimensions shown in the drawing are: A = 50 mm; B = 74 mm; C = 25.4 mm; D = 140 mm; E = 62 mm; and F = 28.6 mm.

Both 1/6-scale prototypes were fabricated, and photographs showing the prototype filled with foam-supported carbon are shown in Figure 3. The granular-sorbent prototype assembly looks similar, and the sorbent-bed dimensions are identical: 50 mm (width) x 25.4 mm (height) x 50 mm (length).

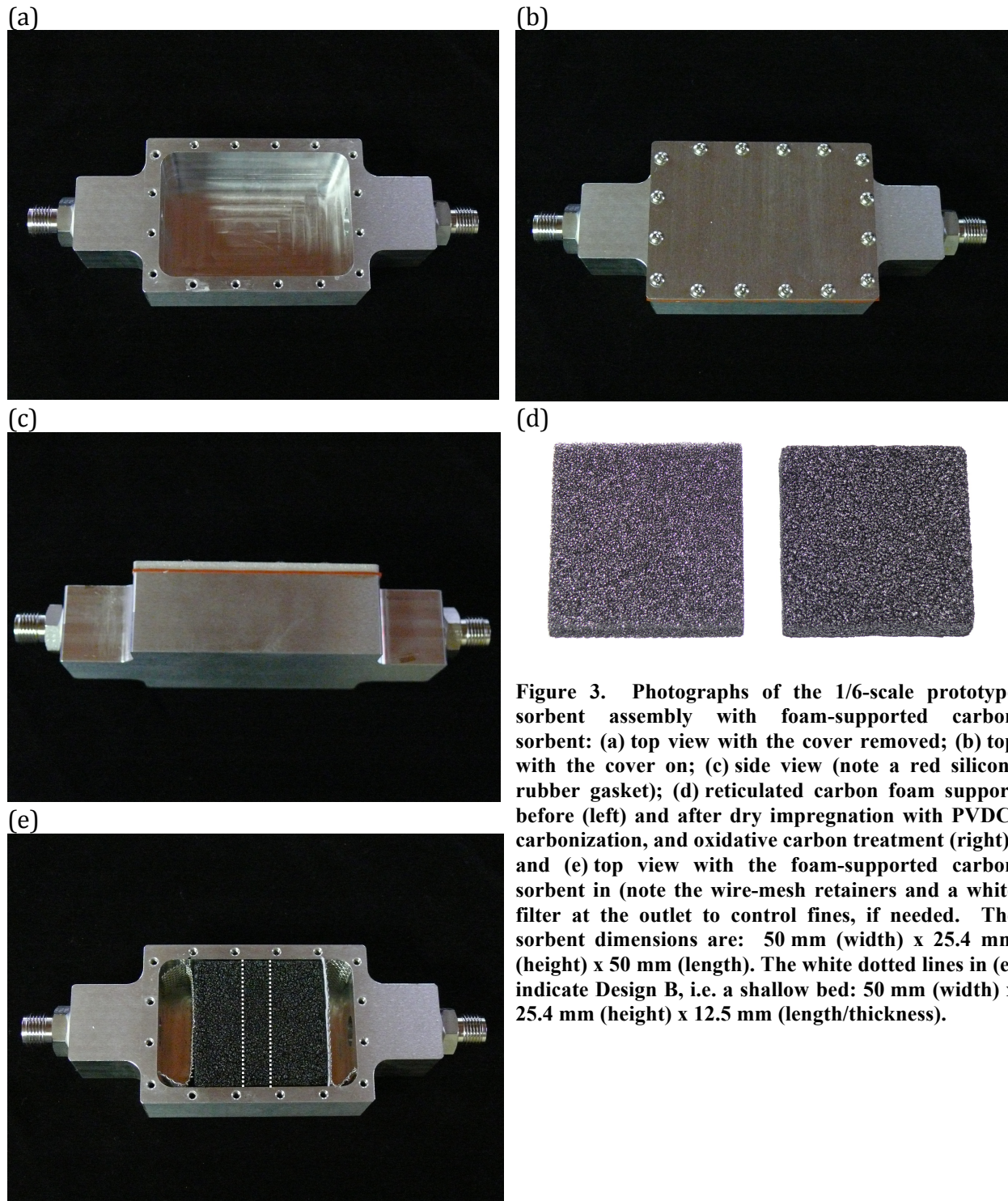


Figure 3. Photographs of the 1/6-scale prototype sorbent assembly with foam-supported carbon sorbent: (a) top view with the cover removed; (b) top view with the cover on; (c) side view (note a red silicon-rubber gasket); (d) reticulated carbon foam support before (left) and after dry impregnation with PVDC, carbonization, and oxidative carbon treatment (right); and (e) top view with the foam-supported carbon sorbent in (note the wire-mesh retainers and a white filter at the outlet to control fines, if needed). The sorbent dimensions are: 50 mm (width) x 25.4 mm (height) x 50 mm (length). The white dotted lines in (e) indicate Design B, i.e. a shallow bed: 50 mm (width) x 25.4 mm (height) x 12.5 mm (length/thickness).

3. Design B: Shallow Sorbent Bed with a Rectangular Cross-Section

The question of implementing a shallow-bed ("pancake") TCC assembly geometry was considered in order to ensure low pressure drop to meet NASA specifications. It was suggested that the best way to address this problem was by including inlet and outlet headers in the unit design, with inlet and outlet ports located on different sides of the assembly.

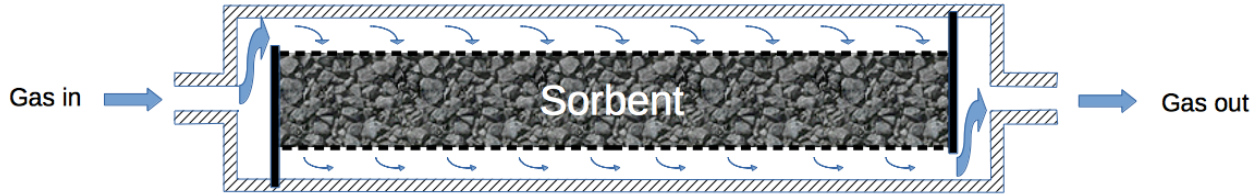


Figure 4. A conceptual design of the prototype TCC unit comprising a shallow sorbent bed for reduced pressure drop.

The conceptual design of the shallow-bed sorption assembly is presented in Figure 4. It schematically shows baffles to direct the gas flow through the sorbent, but the gas flow can alternatively be directed through channels machined into the ends of the aluminum housing, as shown in Figure 5. Photographs of the shallow bed assembly main body, fully assembled with a bare foam panel (100 mm x 12.5 mm x 50 mm), are shown in Figure 5. Figure 5a depicts the top view of the foam sorbent, illustrating the gas flow through the foam panel with green arrows. Figure 5b displays an end view of the assembly, showing the inlet/outlet channels into the sorbent region and pipe plugs used to seal these channels externally.

Ammonia-sorption data collected at UTAS using the granular PVDC-carbon sorbent in the bed shown in Figure 5 (100 mm x 12.5 mm x 50 mm) indicated that the amount of sorbent was so large that the testing time scales were prohibitively long. Consequently, a decision was made to reduce the sorbent volume by a factor of four, and a 1/6-scale TCC housing shown in Figure 2 and Figure 3a-c was fitted with a foam-supported carbon sorbent having the following actual dimensions: 12.5 mm (thickness) x 49 mm (width) x 24.5 mm (height). This design configuration is shown in Figure 3e using white dotted lines. It should be noted that although the aluminum housing for this subscale prototype was originally meant for a deep sorbent bed, Design B is clearly a shallow-bed arrangement because a relatively thin layer of sorbent is placed in a perpendicular direction with respect to the gas flow. In this way, most of the volume of the aluminum enclosure is empty, which is just fine from the standpoint of the 1/6-scale sorbent testing. The above shallow-bed 1/6-scale prototype unit (Design B shown in Figure 3e with dotted lines) was characterized with respect to its pressure drop and delivered to UTAS for ammonia-sorption testing.

4. Pressure-Drop Calculations and Measurements

Granular Sorbent

Pressure-drop calculations were conducted for beds of granular sorbents using the Ergun equation,¹⁵ but the pressure drop across the foam-supported sorbent needed to be determined experimentally.

A spreadsheet with pressure-drop calculations was created for the case where a packed bed of granular sorbent is placed in an assembly with a rectangular cross-section. (The concept of the hydraulic diameter was used to extend the treatment of the pressure drop in beds with circular cross-sections to beds with rectangular cross-sections.) Selected results are compiled in Table 1, where the following cases are considered:

- Flow of air at atmospheric pressure at 30 °C (convenient for laboratory testing)
- Flow of oxygen at 4.3 psia at 30 °C (actual PLSS conditions)

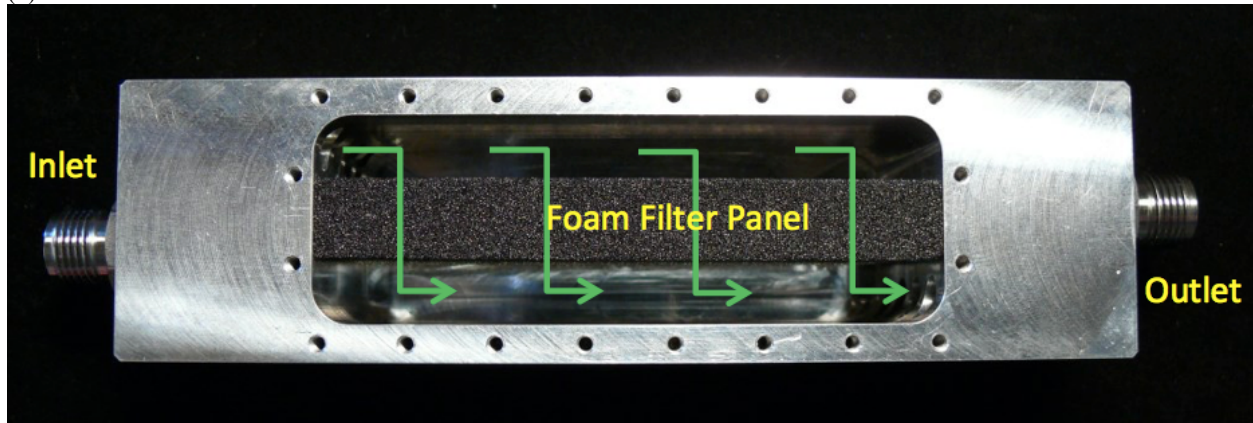
Both cases were considered for the following sets of parameters:

1. Flow rates of 0.75 acfm and 1.0 acfm
(1/6-scale equivalents of full-scale flow rates of 4.5 acfm and 6.0 acfm)
2. Shallow-bed and traditional deep bed geometries:
($W = 7.4$ cm; $H = 5.0$ cm; $L = 2.5$ cm) and ($W = 5.0$ cm; $H = 2.5$ cm; $L = 7.4$ cm), respectively;
 W , H , and L are the bed width, height, and length, respectively
3. Three particle sizes: 0.200 mm, 0.549 mm (+45/-20 mesh), and 3.3 mm

Results of pressure-drop calculations for the flow of oxygen at 4.3 psia at 30 °C were found to be very similar to the case of air at atmospheric pressure at 30 °C, and for this reason only the latter results are presented below. The

important practical implication is that experiments can be conveniently carried out using a flow of air at atmospheric pressure, and the obtained results should provide useful information about the pressure drop for a flow of oxygen at 4.3 psia.

(a)



(b)

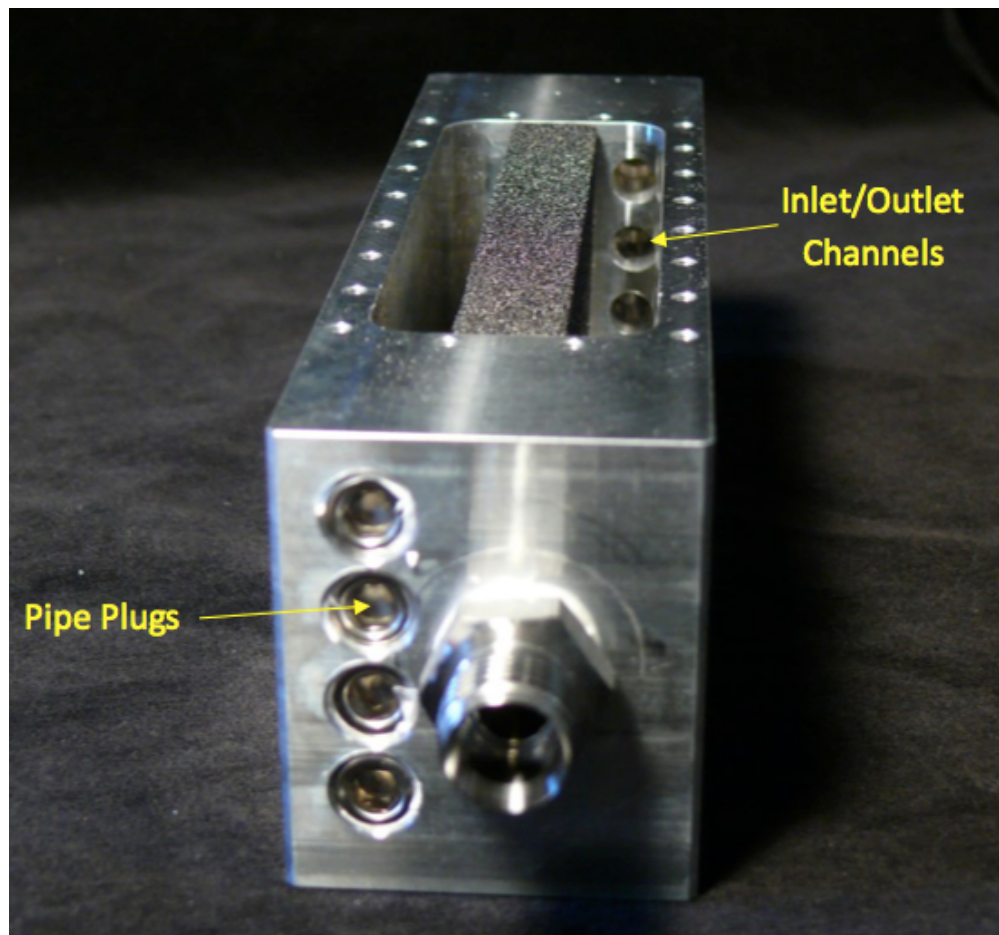


Figure 5. Photographs of a 1/6-scale shallow bed sorbent assembly: (a) top view; and (b) end view.

Table 1. Results of pressure-drop calculations for the 1/6-scale TCC unit for the case of air flow at atmospheric pressure at 30 °C (packed bed with a rectangular cross-section W x H x L).

Design A (traditional deep bed): W = 5.0 cm; L = 7.4 cm; H = 2.5 cm

Particle size (mm)	Δp (in H ₂ O)					$\Delta p/L$ (Pa/m)		Residence time (s)	
	at 0.75 acfm	at 1.0 acfm	D/dp	L/dp	L/D	at 0.75 acfm	at 1.0 acfm	at 0.75 acfm	at 1.0 acfm
0.200	52.05	71.49	167	370	2.22	175,229	240,654	0.261	0.196
0.549	7.99	11.42	61	135	2.22	26,911	38,437	0.261	0.196
3.300	0.46	0.74	10	22	2.22	1,542	2,482	0.261	0.196

Design B (shallow bed): W = 7.4 cm; H = 5.0 cm; L = 2.5 cm

Particle size (mm)	Δp (in H ₂ O)					$\Delta p/L$ (Pa/m)		Residence time (s)	
	at 0.75 acfm	at 1.0 acfm	D/dp	L/dp	L/D	at 0.75 acfm	at 1.0 acfm	at 0.75 acfm	at 1.0 acfm
0.200	5.15	6.93	298	125	0.42	51,281	69,058	0.261	0.196
0.549	0.72	0.98	109	46	0.42	7,162	9,797	0.261	0.196
3.300	0.03	0.04	18	8	0.42	276	409	0.261	0.196

In addition to calculating the pressure drop across the sorbent bed, we also took into consideration dimensioning guidelines for the design of packed beds that ensure plug-flow conditions. The plug flow is generally desirable to eliminate backmixing as well as bypassing and dead zones within the bed. The Ergun equation was used for pressure-drop calculations,¹⁵ and design requirements formulated by Trambouze *et al.*¹⁶ were utilized for plug-flow assessment.

In brief, there are four criteria for a well-developed plug flow:

- $D/D_p > 10$
- $L/D_p > 50$
- $L/D > 0.5$
- $\Delta P/L > 2,500$ Pa/m,

where D is the bed (hydraulic) diameter, D_p is particle diameter, L is the bed length, and ΔP is the pressure drop. Results of computations are shown in Table 1, and cases in which the above plug-flow conditions are violated are marked with red flags next to numerical values listed in the tables.

Data in Table 1 show that, as expected, the shallow-bed configuration is associated with a lower pressure drop than is the case for the traditional deep-bed geometry. Furthermore, the only particle size for which the pressure drop in a shallow bed meets NASA's specifications (< 0.10 in H₂O at 4.5 acfm in full scale; and < 0.20 in H₂O at 6.0 acfm in full scale) is $D_p = 3.3$ mm. For this case, however, three out of four plug-flow conditions are violated (note the red flags in the bottom rows of Table 1). In addition, it is possible that the use of such large sorbent particles (3.3 mm) may be associated with prohibitively long adsorption/desorption time scales due to intra-particle mass transfer limitations. It should be noted that the effect of sorbent particle size on trace-contaminant adsorption can only be studied in a meaningful way in a larger bed.

Results for the traditional deep bed geometry (W = 5.0 cm; H = 2.5 cm; L = 7.4 cm) show that although the plug-flow conditions are almost always satisfied, the pressure drop is well above NASA specifications. In the case of large, 3.3 mm particles, the pressure drop is the lowest, but is still a factor of 3–5 higher than desired.

In view of the above results, it is possible that the existing NASA geometric constraints (11.5" x 7" x 1.8") and pressure-drop constraints are incompatible with a bed of granular sorbent designed for a perfect plug flow. Moving forward, it was recognized that the following choices were possible:

1. Depart from the plug-flow conditions at the expense of sorbent underutilization, which leads to some oversizing of the sorbent bed. This would mean that the plug flow would be imperfect, but an imperfect sorbent-bed design might still work quite well.
2. Replace the granular sorbent with a structured (monolithic or other open-structure) sorbent.

Regarding option (1), this approach may or may not work, depending on the penalties associated with non-optimal sorbent-bed dimensioning. We are unaware of any methods that would make it possible to calculate the

additional amount of sorbent needed if, for example, the L-to-D_p ratio is 50% lower than the one needed for a perfect plug flow. The same can be said about the other plug-flow criteria, and it is fair to conclude that the degree of bed oversizing needed can only be determined experimentally; by trial and error, and in a large scale. Moreover, there is no guarantee that adding sorbent material within the existing constraints will result in meeting NASA specifications and acceptable TCC performance. For example, adding more sorbent due to bed underutilization will be associated with the pressure drop increase, which may eventually exceed the maximum value specified by NASA (0.1–0.2 in H₂O). The maximum bed thickness (1.8”) is a strongly limiting factor, in the sense that additional amounts of sorbent would have to be distributed laterally, thus leading to further departures from the desired ideal plug-flow operation. (The sorbent "pancake" would grow wider, but not any thicker.)

In reference to option (2), the expectation was that the foam-supported carbon sorbent would have a significantly lower pressure drop so that both NASA specifications, TCC volume and pressure drop, can be met simultaneously. This was later verified experimentally (see below).

Pressure-drop measurements for the 1/6-scale TCC assembly shown in Figure 2 and Figure 3 were performed using the apparatus described in reference.⁵ The TCC assembly was filled with the granular PVDC carbon from Entegris, the source gas (dry compressed air) flow rate (1–10 L/min) was regulated using a rotameter, and the pressure immediately upstream of the test sample was measured using a low-pressure diaphragm pressure gauge with a range of 0–10 inches of water. In addition, pressure-drop calculations were performed for a packed-bed of granular sorbent using the Ergun equation [15] and the bed geometry given in Figure 3e (deep bed). The concept of the hydraulic diameter was used to extend the treatment of the pressure drop in beds with circular cross-sections to beds with rectangular cross-sections. Calculations were performed for a flow of air at atmospheric pressure at 30 °C, and for 3.3. mm spherical particles. The actual carbon particles had dimensions close to 2.2 (diameter) x 3.3 mm (height), and it can be shown that the diameter of a sphere that has the same volume as the above cylindrical pellet is 3.3 mm. The fractional voidage of the packed bed was assumed to be 0.39, using for guidance a correlation reported by Benyahia and O'Neill (2005) for cylinders with equivalent sphere diameters between 3.81 mm and 16.60 mm,¹⁷ even though the particles used in our study were somewhat smaller.

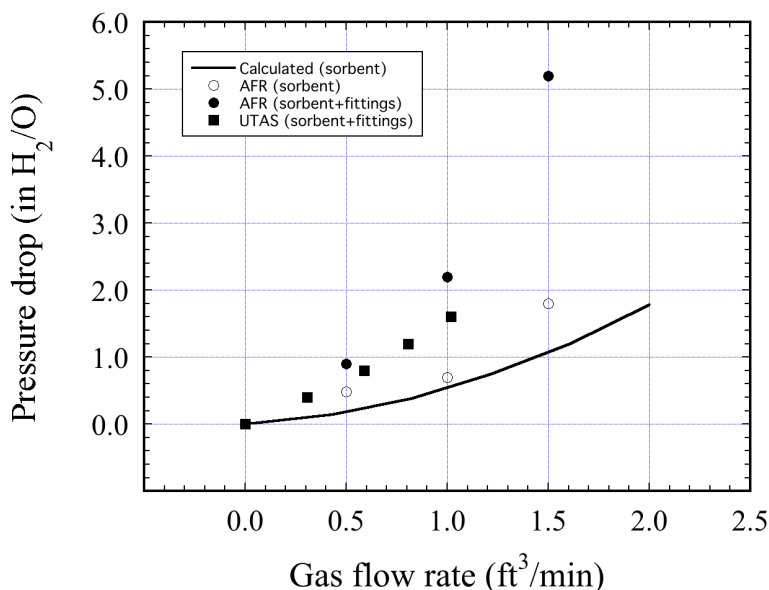


Figure 6. Comparison between calculated and experimentally determined pressure drop across the 1/6-scale TCC prototype containing cylindrical pellets 3.3 mm in diameter and 2.2 mm in height. The sorbent bed dimensions are: 50 mm (width) x 25.4 mm (height) x 50 mm (length), as shown in Figure 3.

The comparison of pressure-drop measurements and calculations is presented in Figure 6, where results of independent pressure-drop measurements performed at UTAS are also included. The calculated values are generally in good agreement with experimental data collected at AFR and UTAS, with calculations somewhat under-predicting the pressure drop. This may be due to the simplifying assumptions made in calculations, and especially

the uncertainty in the value of voidage, to which the Ergun equation is known to be sensitive. As expected, the pressure drop across the sorbent is lower than the pressure drop across the entire assembly.

Results shown in Figure 6 demonstrate that the pressure drop in a traditionally dimensioned packed bed, i.e. in a deep bed, exceeds NASA requirements ($\Delta p < 0.20$ in H_2O), and thus a shallow-bed configuration should be considered instead, even though it may be associated with non-ideal plug flow conditions.

Foam-Supported Sorbent

Pressure-drop measurements were performed at AFR using the entire foam-supported sorbent assembly, including the housing and fittings. From these data, the pressure drop obtained for the TCC assembly without the sorbent were subtracted to obtain the pressure drop contributed by the sorbent foam alone. Results are summarized in Table 2, and their interpretation is presented below. The bed geometry used during the measurements was 49 mm (width) x 24.5 mm (height) x 12.5 mm (thickness).

Table 2. Results of pressure-drop measurements performed at ~25 °C by flowing air through a piece of foam-supported PVDC-carbon sorbent having the following dimensions: 49 mm (width) x 24.5 mm (height) x 12.5 mm (thickness). The data reflect only the contribution to the pressure drop that is made by the sorbent alone, i.e. without the pressure drop resulting from the flow through the fittings, the sorbent housing, and felt filters. K is the friction parameter defined as $K = f/D_p$, where f is the Fanning friction factor and D_p is the characteristic particle diameter (see Eqn. 2).

Input information – yellow fields	Results – blue fields
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Packed Bed with a Rectangular Cross Section

K defined by Eqns 1 and 2 (see also Bird, Stewart and Lightfoot, pp. 196-200 [1])

Enter fluid properties:

Fluid:	air at atmospheric pressure		Requirements for proper plug-flow operation of packed-bed reactors: (see Trambouze <i>et al.</i> , <i>Chemical Reactors</i> , Éditions Technip, Paris, 1988, pp. 390-391 [2])	
Molecular weight (g/mol):	28.84			
Temperature (°C):	25			
Density [3]:	1.1840	kg/m ³		
Cross-section width (W):	0.049	m		
Cross-section height (H):	0.025	m		
Reactor length (L):	0.0125	m		
Reactor hydraulic diameter (D):	0.0327	m	$D/D_p > 10$	<i>Actual</i> undefined
Reactor cross-sectional area (A):	0.00120	m ²	$L/D_p > 50$	undefined
Reactor volume (V):	0.0000150	m ³	$L/D > 0.5$	0.38
			$\Delta p/L > 2,500$ Pa/m	see table

Volumetric flow rate		Superficial velocity v_0 (m/s)	G_0 [kg/(m ² s)]	Δp				$\Delta p/L$ (Pa/m)	Residence time (s)	$K = f/D_p$ (mm ⁻¹)
(L/min)	(m ³ /s)			(in H ₂ O)	(Pa)	(mm Hg)	(psi)			
5.0	8.333E-05	0.099	0.118	0.02	5	0.04	0.001	399	0.180	17.0
10.2	1.695E-04	0.202	0.239	0.05	12	0.09	0.002	996	0.089	10.3
16.0	2.665E-04	0.318	0.376	0.10	25	0.19	0.004	1,993	0.056	8.32
22.3	3.719E-04	0.444	0.525	0.18	45	0.34	0.007	3,587	0.040	7.69
29.5	4.920E-04	0.587	0.695	0.22	55	0.41	0.008	4,384	0.030	5.37

References:

1. Bird, R. B., Stewart, W. E., and Lightfoot, E. N., *Transport Phenomena*, Wiley, New York, 1960.
2. Trambouze, P., Van Landeghem, H., and Wauquier, J. P., *Chemical Reactors: Design/Engineering/Operation*, Éditions Technip, Paris, 1988.
3. The Engineering Toolbox, http://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html; accessed on July 30, 2016.

The pressure drop in a packed bed can be expressed as follows¹⁸:

$$\Delta P = 4f \frac{L}{D_p} \frac{1}{2} \rho v_0^2 \quad (2)$$

where ΔP is the pressure drop, f is the dimensionless Fanning friction factor, L is the bed depth, D_p is the particle diameter, ρ is the gas density, and v_0 is the superficial gas velocity, i.e. the average linear velocity the gas would have in the column if no packing were present. In the case of foam-based sorbent, the nominal particle diameter is difficult to determine, and since both D_p and f characterize the sorbent, it is convenient to use a single "friction parameter" defined as $K = f/D_p$. Equation (1) can now be rewritten as shown below.

$$\Delta P = 4KL \frac{1}{2} \rho v_0^2 \quad (3)$$

It can be seen that, for a given gas density, the pressure drop across the foam-based sorbent is proportional to the foam thickness, L , and the square of the superficial gas velocity, v_0 . The pressure-drop data from Table 2 can now be used to determine the sorbent's friction parameter K , which will make it possible to predict the pressure drop at an arbitrary gas velocity, i.e. at an arbitrary flow rate. It can be seen in Table 2 that K is more or less constant in the middle of the range of flow rates used, but the values calculated for the lowest and the highest flow rates are significantly different. It is believed that this is due to experimental errors associated with operating a gas rotameter close to its lower and upper limits. It seems reasonable to use $K = 8.77 \text{ mm}^{-1}$, which is the average of the three measurements in the middle of the range. Data in Table 2 show that the foam-supported sorbent exhibits a pressure drop compatible with the NASA pressure-drop requirements for gas flow rates up to about $1 \text{ ft}^3/\text{min}$ (29.5 L/min). At higher flow rates, i.e. for prototype assemblies getting close in size to full scale, the sorbent dimensions will be appropriately scaled up to provide the cross-sectional area that ensures meeting the condition: $\Delta P < 0.20$ in H_2O , which should not be too challenging.

5. Ammonia-Sorption Tests Performed at UTAS

Granular Sorbent

The granular-sorbent assembly is described in section III.A.2, and the sorbent bed has the following dimensions: 50 mm (width) x 25.4 mm (height) x 50 mm (length), as shown in Figure 2 and Figure 3. The corresponding bed volume is 63.5 cm^3 , and the weight of the granular sorbent used was 32.07 g.

The first test performed at UTAS involved ammonia sorption on a bed of fresh granular PVDC carbon sorbent. The second test was carried out after regenerating the sorbent overnight in vacuum. The results of these measurements are shown in Figure 7 and Figure 8. Unfortunately, both runs had to be aborted at less than 10% breakthrough because the gas tank containing the ammonia/air gas mixture had been exhausted. These data made it possible, however, to make a rough comparison of the scale-up effort, and it was shown that sorbent performance was consistent with the previously reported data collected in a laboratory-scale reactor.¹²

Further testing of the granular sorbent bed assembly continued at UTAS, and results are presented in Figure 7, Figure 8, and Figure 9. In Tests 1–6, an ammonia inlet concentration of 20 ppm was used, in agreement with the current SMAC values, but since there exists a strong interest in testing sorbent performance at lower ammonia concentrations, Test 7 was performed at an ammonia inlet concentration of 3 ppm. The latter test continued for about 72 hours, i.e. until the breakthrough of 1.5 ppm was achieved. The above conditions are believed to be relevant to future SMAC guidelines.¹⁹ Results of the long-term sorbent testing at a 3 ppm ammonia inlet concentration are shown in Figure 9.

Data presented in Figure 7 and Figure 8 are generally consistent with the laboratory data collected at AFR using a small-scale packed-bed system with order-of-magnitude differences in the residence time and particle size with respect to the UTAS system (residence time: 0.012 s at AFR versus 0.13 s at UTAS; particle size: 0.55 mm at AFR versus 3.3 mm at UTAS). Some reduction in sorbent performance from test to test is evident in Figure 7 and Figure 8, however. This can be explained by the fact that the data in all the tests have been collected at less than 10% breakthrough, which means that the sorbent is still far from achieving its steady-state operation. Since testing with the currently used amount of sorbent (32.07 g) is time consuming, and since large quantities of compressed gas are used, a decision was made to scale down the amount of sorbent in future tests.

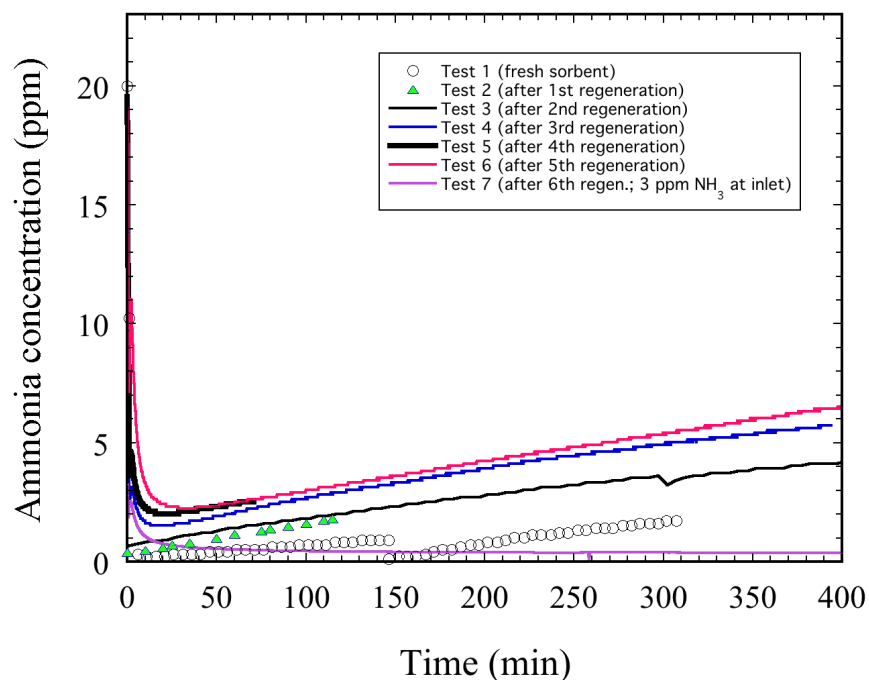


Figure 7. Ammonia breakthrough curves for Tests 1–7 performed at UTAS. The data are for a 1/6-scale prototype unit filled with granular PVDC carbon. The open symbols are for adsorption on the fresh sorbent (Test 1), and the solid symbols are for adsorption on the sorbent regenerated in vacuum (0.06–0.24 torr) overnight (Test 2). Testing was performed at 24 °C, at a gas flow rate of 0.996 ft³/min (actual), and at a dew point of 5.6 °C (RH = 30%).

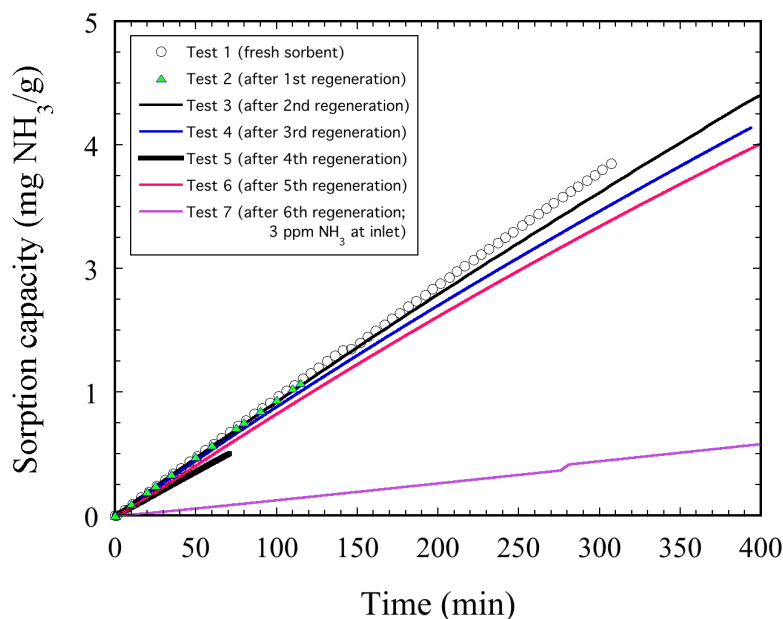


Figure 8. Ammonia-sorption capacity curves for Tests 1–7 performed at UTAS. The data correspond to the breakthrough curves presented in Figure 7, and they are for a 1/6-scale prototype unit filled with granular PVDC carbon.

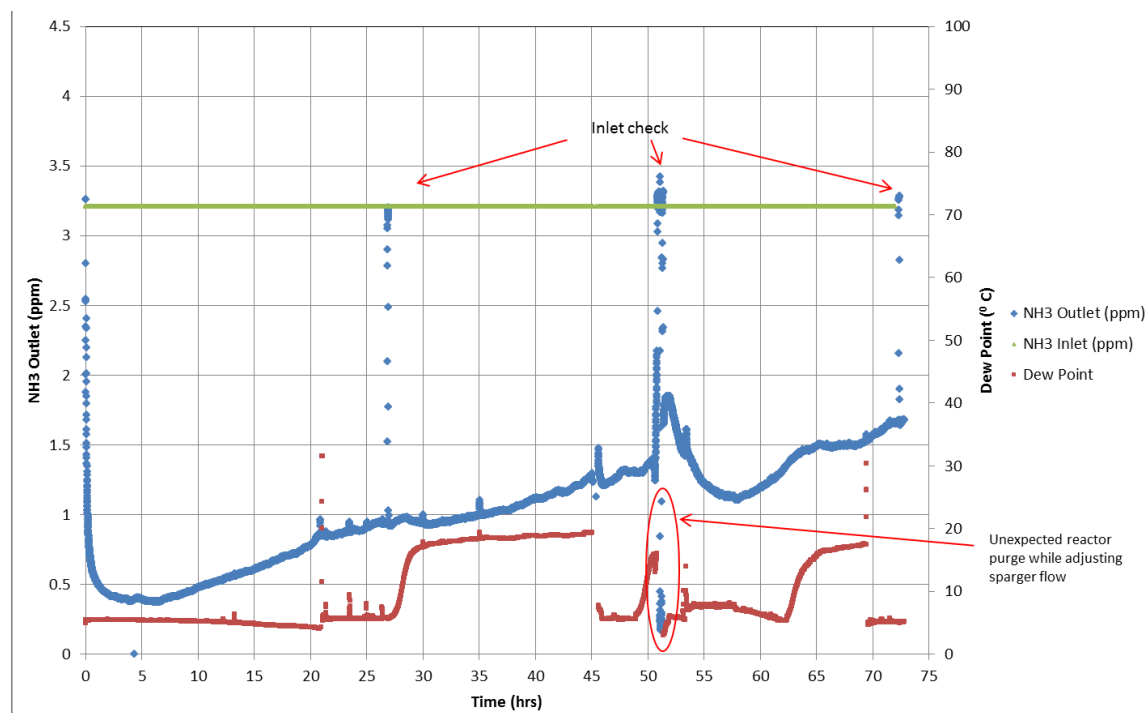


Figure 9. The breakthrough curve and humidity data for a long-duration ammonia sorption run with an ammonia inlet concentration of 3 ppm (Test 7).

Data presented in Figure 9 demonstrate that the modest amount of our granular sorbent (32 g x 6 = 192 g in full scale), in its partially saturated surface condition, i.e. after Tests 1–6, is capable of supporting 9 additional extravehicular activities (EVAs), each 8 hours long, without the need for additional regeneration, and under the challenging condition of only 3 ppm ammonia inlet concentration. These results are deemed encouraging, and they provide additional rationale for reducing sorbent weight in future 1/6-scale tests.

Foam-Supported Sorbent

Tests 8–11 were performed at UTAS using a TCC assembly containing a foam-supported PVDC carbon sorbent. The sorbent dimensions were 49 mm (width) x 24.5 mm (height) x 12.5 mm (thickness), the gas flow rate was 1.0 ft³/min, and the dew point was 5.6 °C (RH = 30%). Results of the above tests are shown in Figure 10.

Tests 8 and 11 were carried out at an inlet ammonia concentration of 20 ppm, whereas the inlet concentration in Tests 9 and 10 was 3 ppm. The purpose of Test 8, which involved ammonia sorption on the fresh carbon surface, was to saturate the sorbent with ammonia prior to tests to be performed at an ammonia concentration of 3 ppm. In this way, results of Tests 9 and 10 can be interpreted as representative for the sorbent that has achieved performance close to steady-state operation after multiple adsorption-desorption cycles. The purpose of the final run (Test 11) was to estimate the steady-state performance of the sorbent at an inlet ammonia concentration of 20 ppm.

It should be noted that the vacuum desorption step after Test 8 was carried out for only 105 minutes rather than the typical minimum 12 hours, and this is why the results of Test 9 show unexpectedly poor sorbent performance. When the problem was realized, Test 9 was aborted, and the sample was vacuum-regenerated overnight. This led to markedly better results in Test 10 (see Figure 10). Data from the final test, Test 11, show that the estimated sorbent capacity at an ammonia concentration of 20 ppm is approximately 19 mg NH₃ per gram carbon, which is certainly consistent with our previously reported lab-scale data collected.^{8,12} Furthermore, this sorption capacity is almost identical to the sorption capacity of Ammonasorb II (~20 mg NH₃ per gram carbon^{3–5}). Both results provide strong evidence of successful sorbent scale-up from lab to 1/6th of full scale.

Results of the test performed at an inlet ammonia concentration of 3 ppm (Test 10) merit a comment regarding further system scale-up to full scale. If performance at 3 ppm ammonia concentration is to be used for guidance, it can be seen from Figure 10 that the sorbent can maintain ammonia concentration below 1.5 ppm for only about 270 min, i.e. 4.5 hours. This means that the amount of the sorbent should be roughly doubled in order to support an eight-hour EVA without the need for sorbent regeneration. This means that the estimated minimum PVDC carbon

amount for a full-scale prototype would be $6 \times 2 \times 1.5 \text{ g} = 18 \text{ g}$, which is close to what we actually used in our full-scale prototype (see section 4 for details). Since the current TCCS guidelines are based on an ammonia SMAC of 20 ppm, however, the minimum PVDC carbon amount for a full-scale prototype is 9.0 g, which means that our full-scale TCC prototype will operate with a comfortable safety margin.

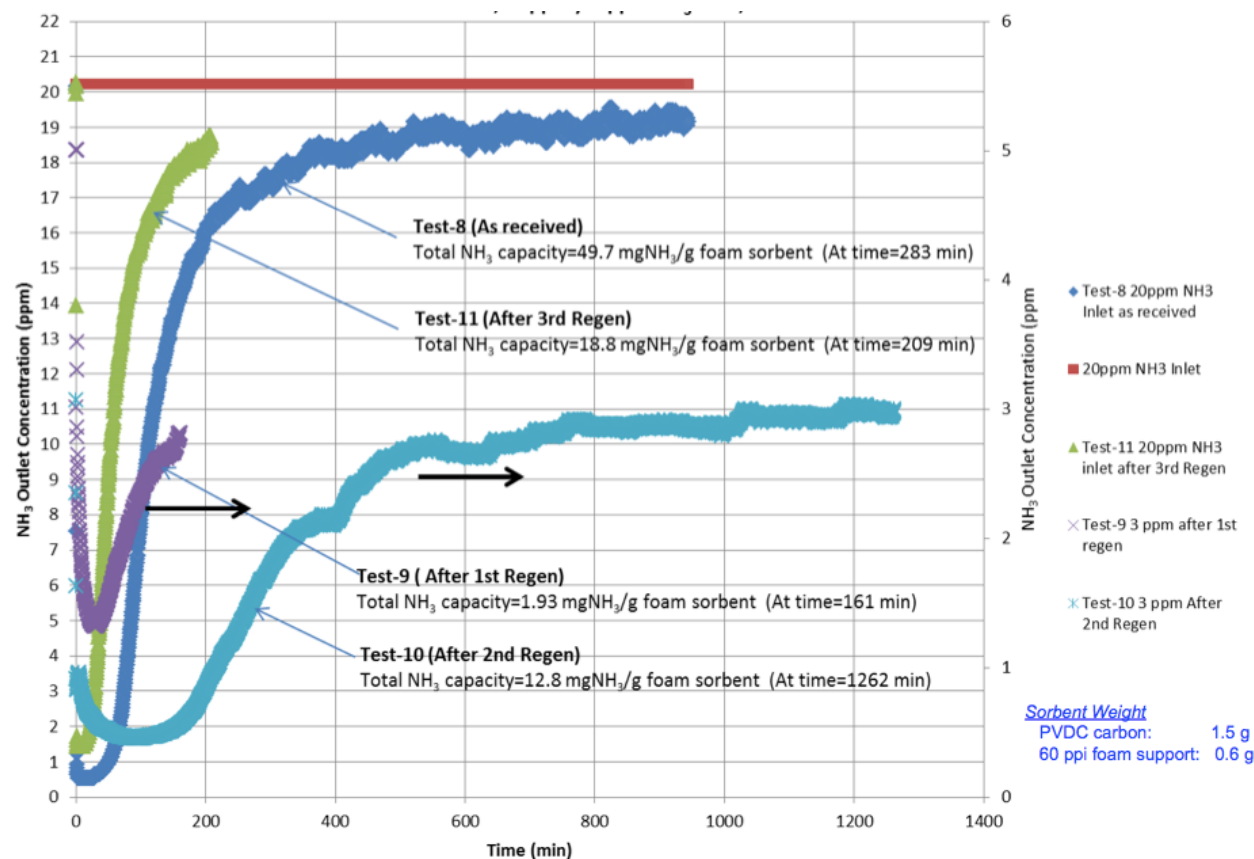


Figure 10. Ammonia breakthrough curves for Tests 8–11 performed at UTAS. The data are for a 1/6-scale prototype unit filled with foam-supported sorbent having the following dimensions: 49 mm (width) x 24.5 mm (height) x 12.5 mm (thickness).

B. Development and Preliminary Testing of Full-Scale Prototypes

1. Design of a Shallow Sorbent Bed with a Rectangular Cross-Section

The pressure-drop calculations for the full-scale TCC unit performed in section III.A.4 led to the conclusion that a shallow bed geometry would be advantageous in order to meet the stringent pressure-drop constraints ($\Delta p < 0.20$ in H_2O). This kind of geometry is normally associated with flow-distribution problems at the inlet and outlet, and the use of a header space on both ends of the prototype assembly is likely to alleviate this challenge, at least partly. The additional space allocated to the headers will have to come at the expense of increased sorbent-bed lateral dimensions (width and length), all within the geometric constraints of the TCC unit (11.5" x 7" x 1.8").

Since at the time of designing the full-scale prototype, 1/6-scale ammonia-sorption data for the foam-supported sorbent were still unavailable, ammonia breakthrough curves collected in a lab-scale system at a 3 ppm ammonia inlet concentration were used for scale-up.¹² It was found that it took about 550 min, i.e. ~ 9.2 hours, for the outlet ammonia concentration to reach ~ 1.5 ppm. This time scale corresponds approximately to a single EVA (typically up to 8 hours), which means that the volume of the sorbent used in lab-scale experiments, V_L , can be scaled up to the sorbent volume in the full-scale system, V_F , simply by multiplying V_L by the ratio of the full-scale to lab-scale volumetric flow rates, i.e. by $(170 \text{ L/min})/(2.4 \text{ L/min}) \approx 71$. Thus, $V_F = 71 \times V_L = 71 \times 1.52 = 108 \text{ cm}^3$. If blocks of foam-supported sorbent used in the past are used, each with dimensions of 10 cm x 5.0 cm x 1.25 cm, then two such

blocks, each having a volume of 62.5 cm^3 , would be sufficient to support a single EVA. It makes sense, however, to apply a significant safety margin by using three rather than two such sorbent blocks, with a total volume of $3 \times 62.5 = 188 \text{ cm}^3$. In this way, the safety factor applied is $188/108 = 1.74$.

Strictly speaking, the approach to sorbent scale-up discussed above is correct as long as the residence times characteristic of the laboratory and full-scale systems are not too different. This is usually difficult to accomplish experimentally, and this is why there is some uncertainty associated with scale-up. The residence time calculated for the lab-scale system is 0.038 s, whereas the corresponding value for the full-scale shallow bed of dimensions 10 cm (height) x 15 cm (width) x 1.25 cm (thickness) is 0.066 s. (The latter bed geometry corresponds to three blocks of foam 10 cm x 5.0 cm x 1.25 cm stacked side by side, and the flow rate for the full-scale system is assumed to be 170 L/min.) It can be seen that the residence time for the full-scale system is somewhat larger than for the lab-scale system, which means that the full-scale system should perform slightly better.

The suggested shallow-bed arrangement of the three sorbent-foam blocks is shown in Figure 11. The advantage of the shallow-bed design is low pressure drop, but the distribution of the gas flow at the TCC-unit inlet may be problematic, which can be at least partly addressed through the use of head space, as shown in Figure 4. A detailed design of the full-scale sorbent assembly shown schematically in Figure 11 was prepared. Figure 12 depicts 3D drawings of the main body of the sorbent assembly, which is machined from a single aluminum block. As shown in the solid view (Figure 12a), the overall dimensions of the housing are 220 mm (length) x 45 mm (width) x 109 mm (height). The inside dimensions of the region that supports the sorbent are 150 mm (length) x 33 mm (width) x 102 mm (depth). The design calls for positioning the sorbent longitudinally along the center of this region.

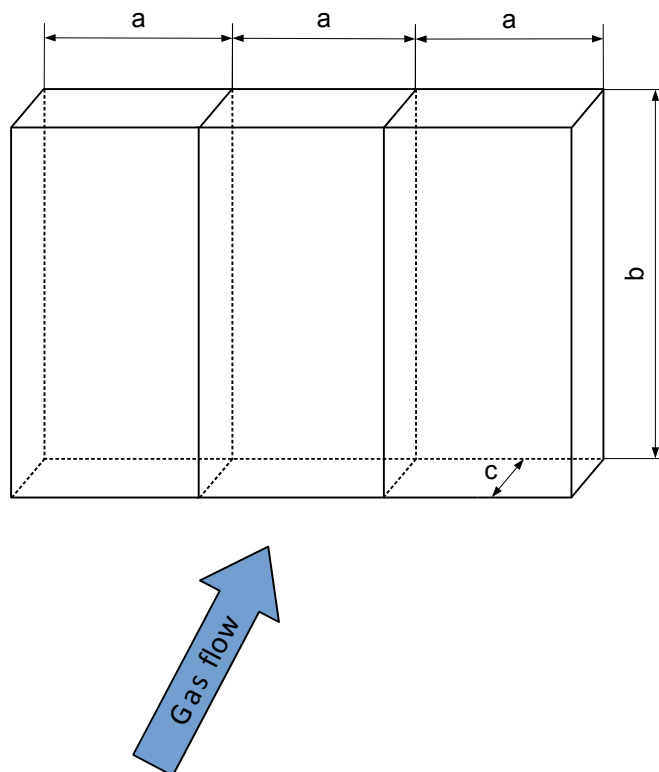


Figure 11. Schematic representation of three sorbent-foam blocks for the prototype full-scale TCC assembly. The dimensions are: $a = 5.0 \text{ cm}$, $b = 10 \text{ cm}$, and $c = 1.25 \text{ cm}$.

In the design shown in Figure 12, the gas flow is directed through channels machined into the ends of the aluminum housing. As shown in the wire-frame drawing (Figure 12b), the inlet gas (represented by the blue arrows) enters the TCC assembly from two opposite ends of a channel drilled in the aluminum housing. In this flow configuration, the inlet gas is split into two streams, which should facilitate better gas-flow distribution at the inlet. In an alternative arrangement, the entire gas flow may enter the TCC assembly through a single inlet port, the other one being plugged. The latter configuration is simpler, and it may be advantageous if the gas-flow distribution

proves not to be a problem. Similarly, the outlet gas flow may be directed either through two outlet ports, as shown by the red arrows in the left drawing in Figure 12b, or through a single port, with the other port plugged. Gas-flow distribution is of little or no concern at the outlet of course, but there may be differences in the pressure drop that may justify the choice of one flow configuration over the other. Having entered the TCC assembly through one or two inlet ports, the gas is injected into the sorbent-assembly chamber through eight parallel channels located on one side of the housing. (Note that all of the channels of the TCC assembly include pipe threads, some of which are plugged, as marked in red in Figure 12a.)

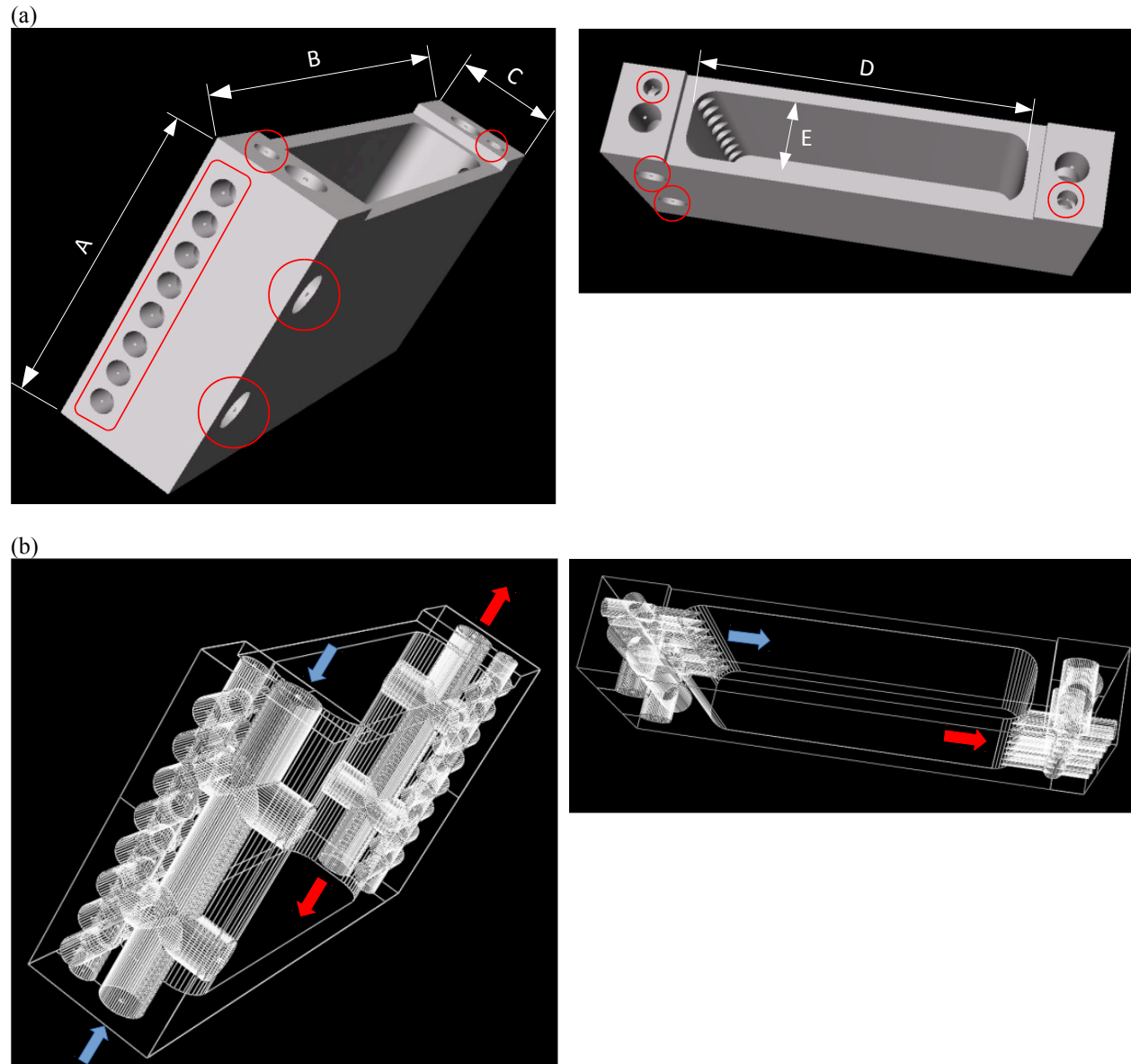


Figure 12. (a) 3D solid-frame view of the full-scale shallow-bed sorption assembly; the dimensions are: A = 109 mm; B = 220 mm; C = 45 mm; D = 150 mm; E = 33 mm. The depth of the sorbent compartment is 102 mm. The holes that are meant to be plugged are encircled with red lines. (b) 3D wire-frame view of the shallow-bed sorption assembly, showing the internal gas channel geometry for distributing the gas. The inlet and outlet gas flow is illustrated by the colored arrows: blue - gas inlet; red - gas outlet.

Table 3. Results of pressure-drop calculations performed for a piece of foam-supported PVDC-carbon sorbent having the following dimensions: 150 mm (width) x 100 mm (height) x 12.5 mm (thickness); see Figure 11. The data reflect only the contribution to the pressure drop that is made by the sorbent alone, i.e. without the pressure drop resulting from the flow through the fittings, the sorbent housing, and felt filters. K is the friction parameter defined as $K = f/D_p$, where f is the Fanning friction factor and D_p is the characteristic particle diameter (see Eqn 2). Input information is highlighted in yellow, and results in blue.

Case	Volumetric flow rate		Superficial velocity v_0 (m/s)	G_0 [kg/(m ² s)]	Δp				$\Delta p/L$ (Pa/m)	Residence time (s)
	(L/min)	(m ³ /s)			(in H ₂ O)	(Pa)	(mm Hg)	(psi)		
Air at 1 atm	170.00	2.833E-03	0.251	0.297	0.065	16	0.12	0.0024	1,303	0.066
O ₂ at 4.3 psi	170.00	2.833E-03	0.251	0.297	0.021	5.2	0.04	0.0008	418	0.066

The pressure drop for the full-scale sorbent assembly shown in Figure 11 can be calculated from Eqn. 3 using the value of K determined from the pressure-drop measurements presented in Table 2 ($K = 8.77 \text{ mm}^{-1}$). The calculations were performed for the following two cases: (1) air at atmospheric pressure (probably more relevant for initial testing at NASA Johnson Space Center); and (2) oxygen at 4.3 psi (relevant to actual PLSS conditions). Results are shown in Table 3, and it can be seen that the pressure drop is less than 0.10 in H₂O, which is well below the NASA requirement of 0.20 in H₂O. The fact that the plug-flow requirements given by Trambouze *et al.*¹⁶ ($\Delta p/L > 2,500 \text{ Pa/m}$; $L/D > 0.5$) are not met is hardly surprising as shallow beds are not expected to operate under perfect plug-flow conditions. On the other hand, the plug-flow requirements listed in reference¹⁶ were originally formulated for beds of granular material, and it is believed that the foam-supported sorbent will be less prone to channeling than a packed bed of granular sorbent. Furthermore, the lack of perfect plug flow does not necessarily mean that the sorbent will not operate properly. Clearly, the choice of a shallow-bed configuration is a result of the compromise between the adherence to traditional design guidelines and the need to meet NASA's stringent pressure-drop specifications.

2. Full-Scale Prototype Construction

Two full-scale prototypes were fabricated according to the design shown in Figure 11 and Figure 12, each containing one of the following sorbents: (1) granular PVDC carbon oxidized in air at 325 °C for 44 hours (92.91 g of cylindrical pellets ~3.3 mm in diameter and ~2.2 mm in thickness); and (2) Allied Signal PVDC carbon supported on 60 ppi Duocel® foam, oxidized at 350 °C for ~20 hours (17.08 g of PVDC carbon + 8.65 g of foam support). In both cases, the sorbent bed volume was about 190.5 cm³.

Figure 13 depicts images of the machined TCC assembly housing, prior to loading it with either the granular or foam-supported sorbent. The images also show the various pipe plugs used to seal the gas channel drill holes, as well the tube adapters for connecting the filter housing to the NASA test rig.

The sorbent occupies an approximately 150 mm x 102 mm x 12.5 mm region in the center of the filter housing. Both the granular and foam-supported sorbents are supported in the housing in similar fashion, as shown schematically in Figure 14. In both cases, the sorbents are sandwiched between two separate perforated aluminum sheets (0.32" thickness, 0.25" diameter holes). For the foam-supported sorbent, the perforated sheet is angled at the bottom, to assure centering inside the housing when installed. For the granular carbon, several stainless steel screws are employed as stand-offs for centering as well as to maintain shape within the housing. Polypropylene filter fabric (0.02" thickness, 100 micron particle retention) is also located on each side, between the sorbent and perforated sheet. Figure 15 illustrates the sequence of steps for loading the housing with granular sorbent, and Figure 16 shows the fully assembled TCC prototype.

3. Full-Scale Prototype Testing

Preliminary testing of the deliverable TCC prototypes at AFR focused on leak testing and pressure drop measurements. Sorption-performance testing of full-scale prototypes involves long time scales and high flow rates (~170 L/min), and neither AFR nor UTAS has the appropriate test rig. For this reason, final testing will be conducted at NASA Johnson Space Center and results will be reported in a separate publication.

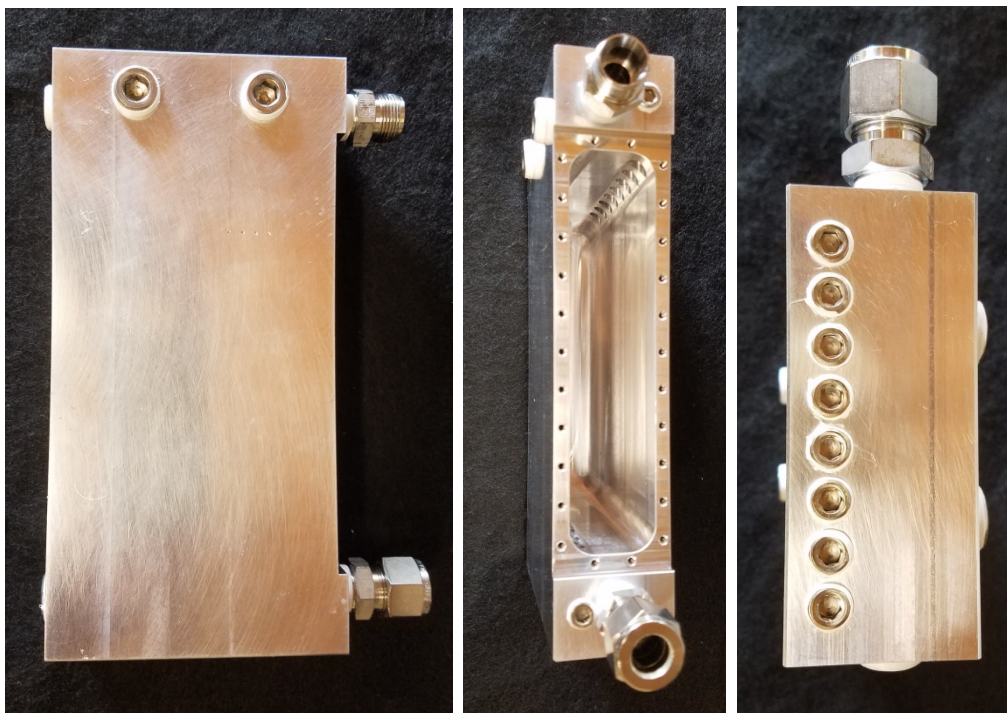


Figure 13. Side, top and end views of the TC sorbent housing, with pipe plugs and tubing adapters installed.

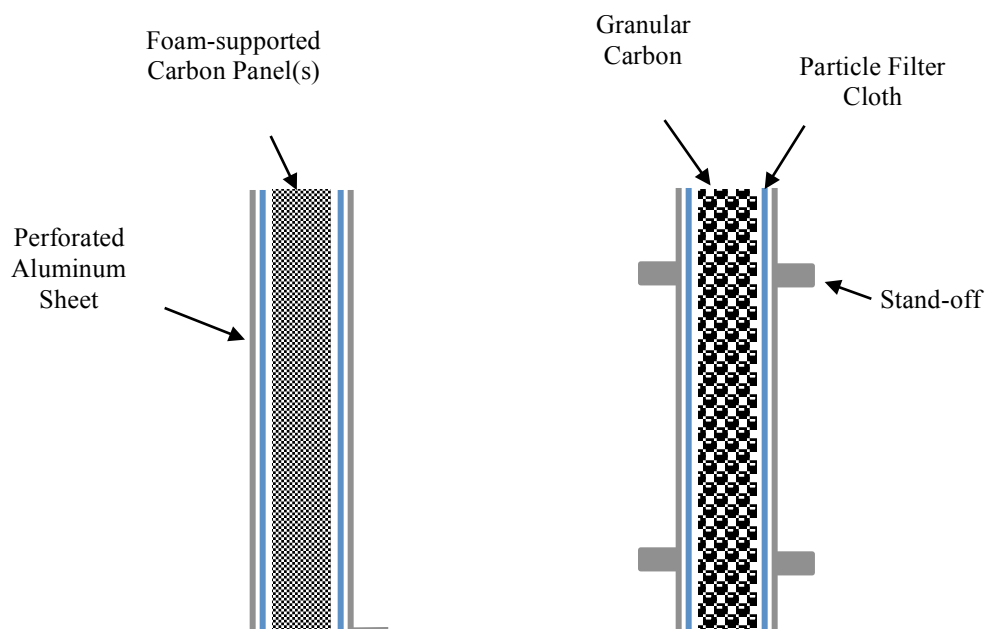


Figure 14. Schematics of the support structures for holding the sorbents inside the housing.

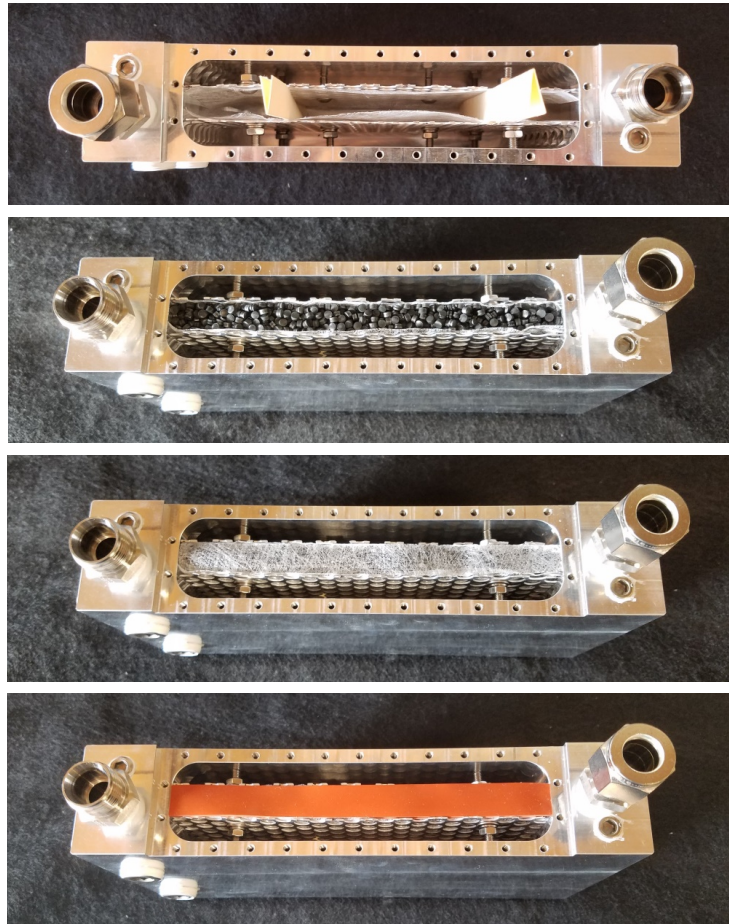


Figure 15. Installation of the granular sorbent inside the housing.

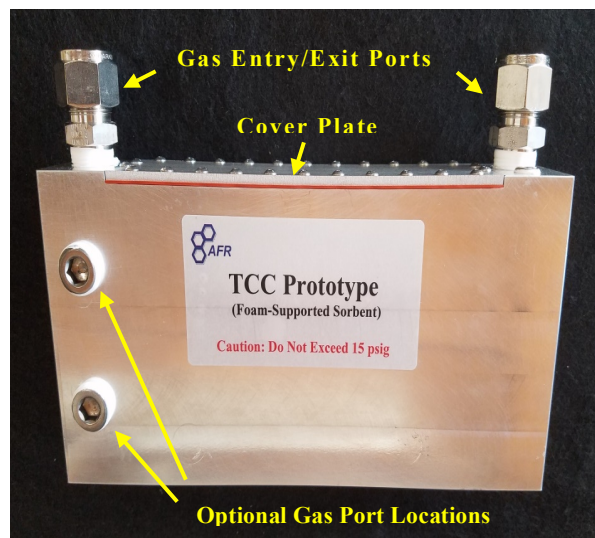


Figure 16. Prototype TCC assembly showing gas entry/exit locations

Leak testing was performed using the pressure decay method. Each prototype assembly was pressurized to about 15 psi (nitrogen), and the pressure was monitored for several hours. For each device, no measureable decrease in pressure was observed.

Pressure drop measurements were recorded over a range of 2–5 cfm in 1 cfm increments. The flow rate was measured using a King Instruments rotameter (2–20 cfm range), and the pressure was monitored with a Noshok dial pressure gauge with a range of 0–10 in H₂O. Measurements were compared for three cases: (1) an empty housing; (2) the housings with the perforated screen and filter fabric components; and (3) the housings with the screen, fabric, and sorbent. Table 4 summarizes the results.

Table 4. Pressure drop measurements for the deliverable prototype assemblies.

Flow Rate (cfm)	Pressure Drop (in H ₂ O)				
	Housing (empty)	Foam-Supported Sorbent Assembly		Granular Sorbent Assembly	
		Housing + Perf. Sheet + Filter	Housing + Perf. Sheet + Filter + Sorbent	Housing + Perf. Sheet + Filter	Housing + Perf. Sheet + Filter + Sorbent
1	0.5	0.5	0.5	0.5	0.5
2	1.15	1.1	1.15	1.1	1.1
3	2.0	2.0	2.0	2.0	1.95
4	3.1	3.1	3.1	3.0	3.0
5	4.5	4.5	4.5	4.3	4.3
6	6.2	6.2	6.2	5.9	5.85

It can be seen from the data that neither the perforated screen and particle filter fabric nor the sorbent adds any measurable pressure drop and that the major pressure drop is attributed to the housing-tubing connectors. It should be noted that this research program focused on the development of the carbon sorbent that, by itself, exhibited acceptable pressure drop. The two constraints in designing the housing were that it meet the size restrictions defined by NASA, and that it could be fabricated using traditional machining methods. The disadvantage of this approach was that the gas flow at the entry and exit ports involved multiple bends, with limitations on the bore diameter. Using a combination of welding and machining, for example, would potentially enable a simpler flow path with a larger bore. This would result in a housing design with a much lower pressure drop, and the optimization of the sorbent enclosure will be the subject of future work.

IV. Conclusions

Two subscale prototypes were designed, constructed, and tested for pressure drop and ammonia-sorption performance. It was found that the traditional deep-bed design would be associated with excessive pressure drop, and an alternative, shallow-bed design was chosen. One of the subscale prototypes contained 32 g of granular PVDC-derived carbon in the form of cylindrical pellets ~3.3 mm in diameter and ~2.2 mm in thickness. The sorbent occupied 63.5 cm³ of prototype volume. The second subscale prototype was loaded with PVDC carbon (1.5 g) supported on vitreous carbon foam (0.6 g) having the following dimensions: 49 mm (width) x 24.5 mm (height) x 12.5 mm (thickness). Ammonia-sorption data were found to be consistent with the previously reported laboratory sorbent performance results,^{8,12} and the experience gained running the subscale prototypes was used for further scale-up.

Two full-scale TCC prototypes were designed, constructed, tested for pressure drop, leak-tested, and delivered to NASA Johnson Space Center. One prototype contained 93 g of granular PVDC carbon sorbent, and the sorbent loaded into the second prototype was PVDC carbon supported on carbon vitreous foam (17.1 g of PVDC carbon + 8.65 g of foam support). In both prototype TCC assemblies, the sorbent bed volume was about 190 cm³. Pressure-drop measurements performed at AFR showed that the pressure drop on our sorbent beds was negligible as compared with the resistance to the flow offered by the sorbent enclosure. The full-scale prototypes are expected to provide trace-contaminant capture for at least one EVA, which will be followed by sorbent regeneration on board spacecraft.

Future work will focus on testing of full-scale prototypes over hundreds of adsorption-desorption cycles, and this work will be performed at NASA Johnson Space Center. Future research and engineering will also address the following topics: (1) improvements in the effectiveness of sorbent regeneration; (2) optimization of sorbent housing design and piping to reduce pressure drop; and (3) integration of the TCCS with the PLSS.

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